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Scale Dependence in the Dynamics of Earthquake Rupture Propagation: Evidence from Geological and Seismological Observations

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1 - Definition: Dynamic Fault Weakening:

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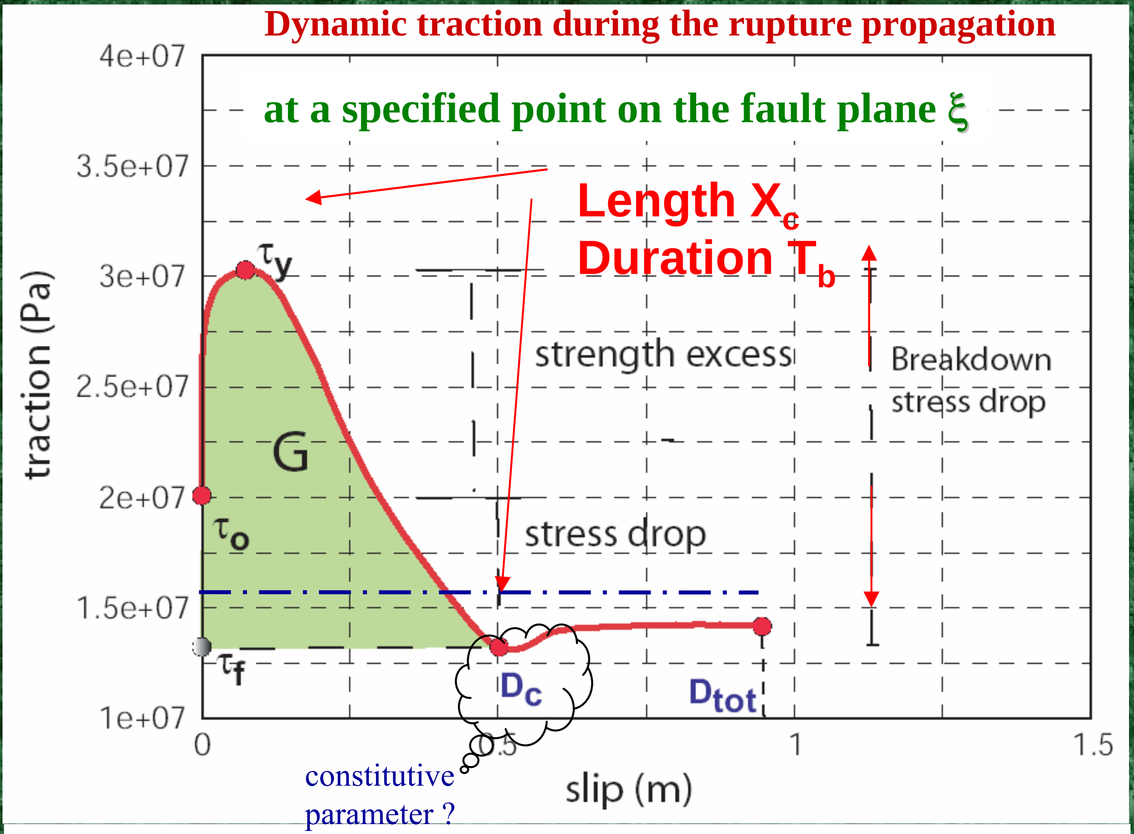
- An earthquake consists of a dynamic instability described by the shear traction evolution with time or slip
- Dynamic traction evolution can be very complex, but
  - to have a finite stress
  - to radiate seismic waves
  - to dissipate part of the total strain energy on the fault
- the traction has to decrease from τ_y to τ_f in a finite time T_b



A common behavior of dynamic traction evolution

$$G = G(\delta) = \int_0^{D_c} \left[\tau(\delta') - \tau_{res}\right] d\delta'$$

Fracture Energy

Statement #1
Seismologists need tractions

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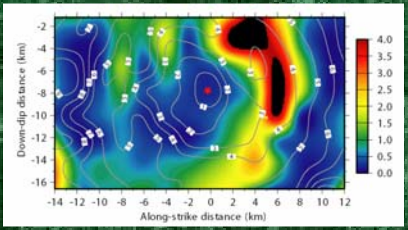
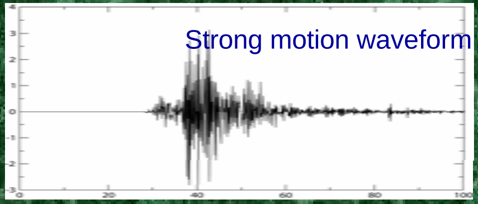
- To apply fracture mechanics to earthquakes and faulting on virtual mathematical planes
- To simulate numerically spontaneous dynamic earthquake propagation



- To model seismic wave generation and to predict ground shaking



- To understand the earthquake energy balance

Observation #1
Fracture Energy from Seismology

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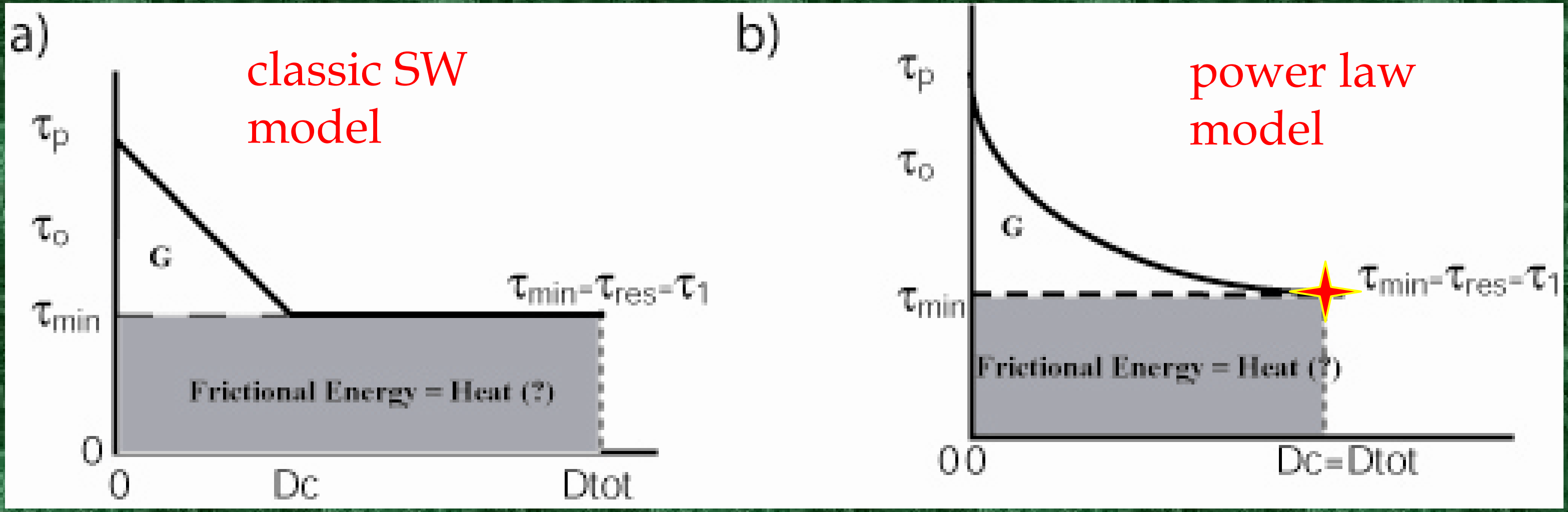
- From a seismological point of view it is required that a portion of the mechanical work absorbed on the fault must be the energy that sustains dynamic rupture propagation
- G account for all the dissipation in excess to $\tau_{res} \cdot \Delta u_1$



Ida (1972); Palmer & Rice (1973) Andrews (1976-a, -b) (Abercrombie & Rice, 2005)

Observation #2
Surface Energy from Geology

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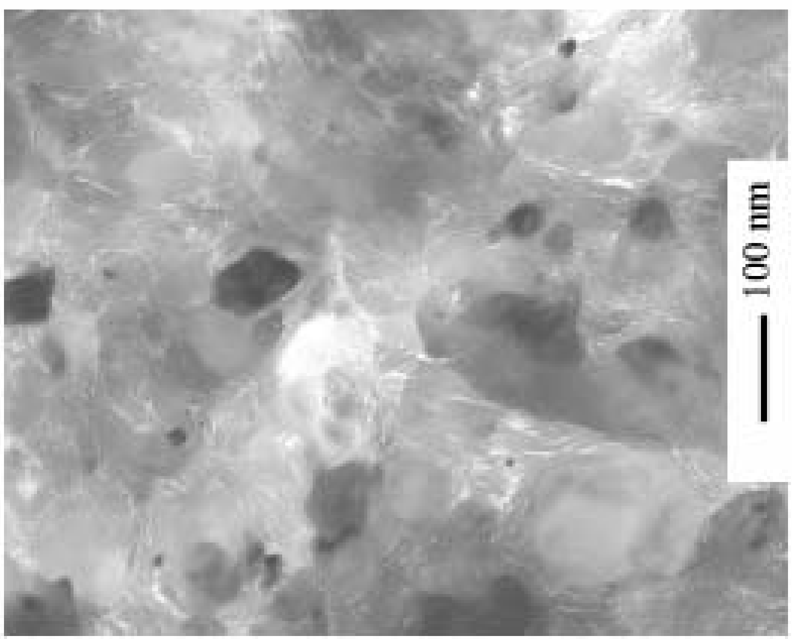
Chester and her colleagues determined the surface area of all the grains in the fault zone. Multiplying this area by 1 J/m^2, the single-crystal fracture energy, they determined the total surface energy of the fault zone (accumulated in about 10000 earthquakes).

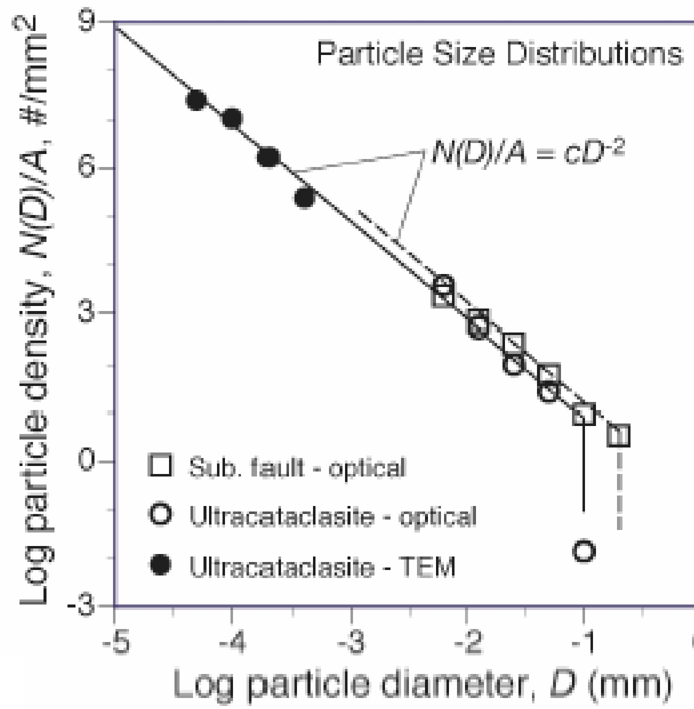
Wilson et al. (2005) determined the particle size distributions and total surface area of the rock flour in the Bosman fault and in the pulverized granite zone of the San Andreas fault.

TEM image of ultracataclasites showing particles 10 - 200 nm in diameter



Chester, Chester, and Kronenberg, Nature, 2005

Ultracataclasite particle size distribution



Observation #3
Fault Zone Structure

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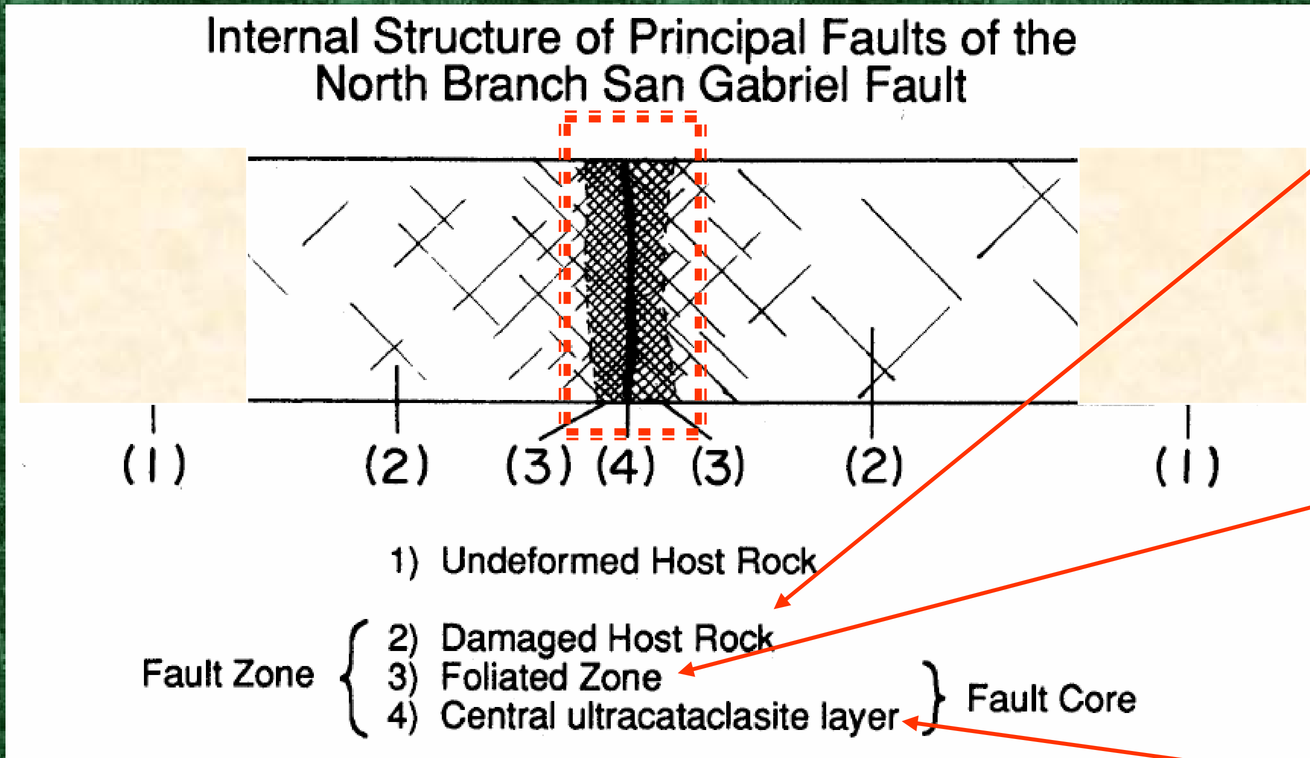

Fig. 2. Schematic section across the North Branch San Gabriel fault zone illustrating position of the structural zones of the fault. The diagram is not to scale.

30-100 m
(damage ≈ *highly cracked rock*. Zone with macro faults or fractures extends ~ 10x further.)

1-10 m
(sometimes described as *foliated gouge*, or for some faults, simply as *gouge*.)

10s-100s mm
(but ***principal failure surface*** is *much thinner*, typically < 5 mm!)

Chester, Evans and Biegel, *J. Geoph. Res.*, **98** (B1), 771-786 (1993)
Rice and Cocco, *Dahlem Conference* book, MIT press (2006)

Observation #4 - Experimental faults: insights from laboratory experiments

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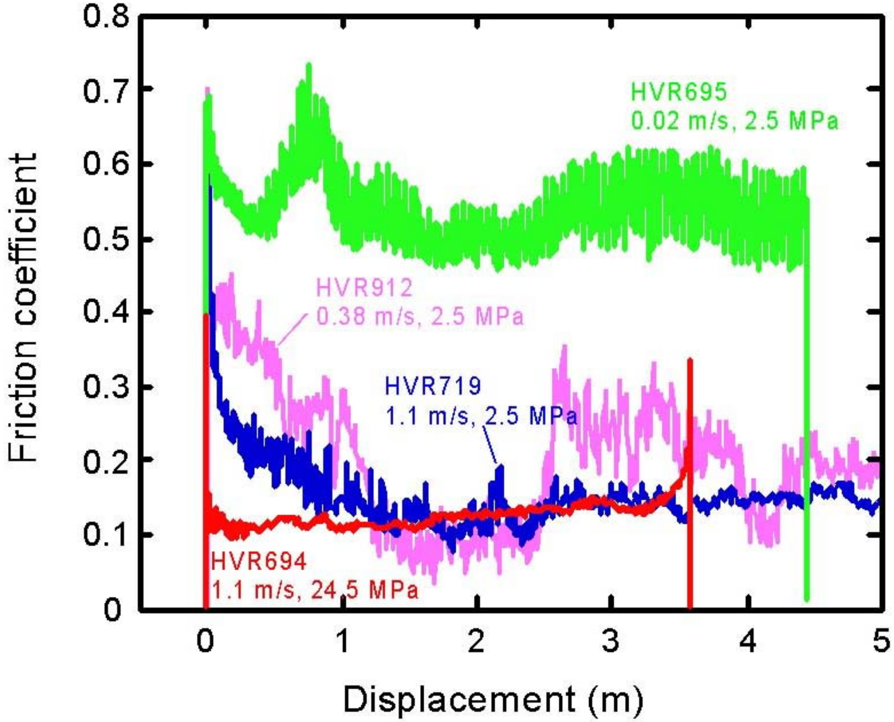
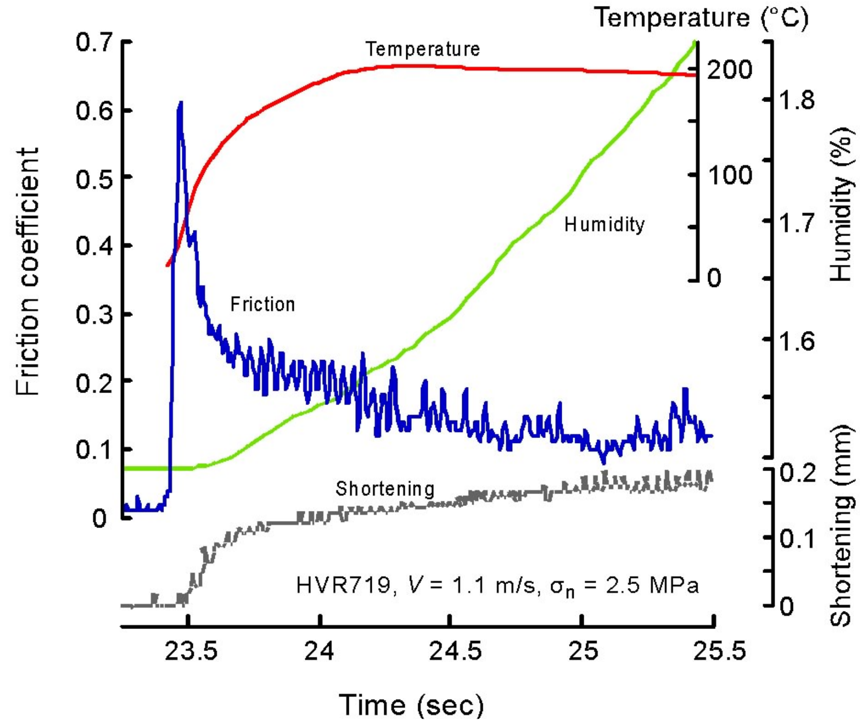
Takehiro Hirose and Misha Bystricky, GRL, Vol. 34, 2007



Representative frictional coefficient versus displacement curves from HVR experiments on serpentinite.



Mechanical data at normal stress of 2.5 MPa and slip velocity of 1.1 m/s, plotted together with change in measured humidity, axial shortening of specimen due to gouge extrusion from sliding surfaces and calculated maximum temperature on sliding surfaces.

Statement #2
Crack driving force

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- From seismology: it is required that a portion of the mechanical work absorbed on the fault plane must be the energy that has to sustain the dynamic rupture propagation
- Numerous theoretical models consider the fracture energy G as the crack driving force
- The concept of crack driving force is commonly associated with the energy release rate, which is unambiguously defined for crack models having a stress singularity at the propagating tip or for non-singular cohesive rupture models characterized by an infinitesimal breakdown zone size

Implications #1

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- Earthquakes associated with such a fault zone structure have to be scale dependent
- This should imply a departure from self-similarity
- If earthquake processes are scale dependent, there must exist a discrete hierarchy of such characteristics length scales in order to make them consistent with the overall self-similarity of earthquakes
- Both fracture energy and the slip weakening distance (Dc) are scale dependent

A Previous Study

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- Ohnaka (2003) proposed that the characteristic length scale parameter is the predominant wavelength that represents geometric irregularity (or roughness) of the rupturing surfaces in the slip direction

$$D_c = \mathrm{K}(\,\Delta\tau_b / \tau_y\,)^m \lambda_c$$

- However, there are <u>many other length scale parameters</u> associated with other dissipative processes that can affect the dynamic fault weakening

GOALS & DREAMS

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- For all these reasons we believe that it is important to reconcile a theoretical understanding of earthquake energy balance with current geologic understanding of fault zone structure and seismological fracture energy measurements

- The challenge is to success in understanding those processes controlling gouge & damage evolution and in representing them through physical constitutive laws at their proper scales

CAVEAT

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- **No theoretical solutions are available today for a physically consistent renormalization of earthquake rupture dynamics based on an accurate representation of the physics of the dissipation processes occurring at different scales**

- **One simple reason for this lack of a complete physically-consistent description of earthquake dynamics is the poor knowledge of the constitutive laws governing each process occurring within the fault zone and controlling strain localization, dynamic fault weakening and stress evolution**

- Dynamic earthquake ruptures occur within a fault zone volume and on interfaces of finite thickness and involve various non linear dissipation processes coupled over a wide range of spatial and temporal scales

- Because most of our understanding of dynamic earthquake ruptures relies on frequency-dependent seismological observations, this raises the question of the scale dependence and scale separation during earthquakes

A phenomenological approach

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- In the absence of such a detailed physical description of a scale dependent process, we are forced to use in seismology classical continuum mechanics and a phenomenological approach to describe dynamic fault weakening and rupture propagation on a virtual mathematical plane of zero thickness.
- This implies that shear stress, slip and slip velocity should be considered as macroscopic parameters. In this context fracture energy and slip-weakening distance (D_c) are scale dependent parameters not directly associated with the processes occurring at smaller scales.

A Macroscopic Description

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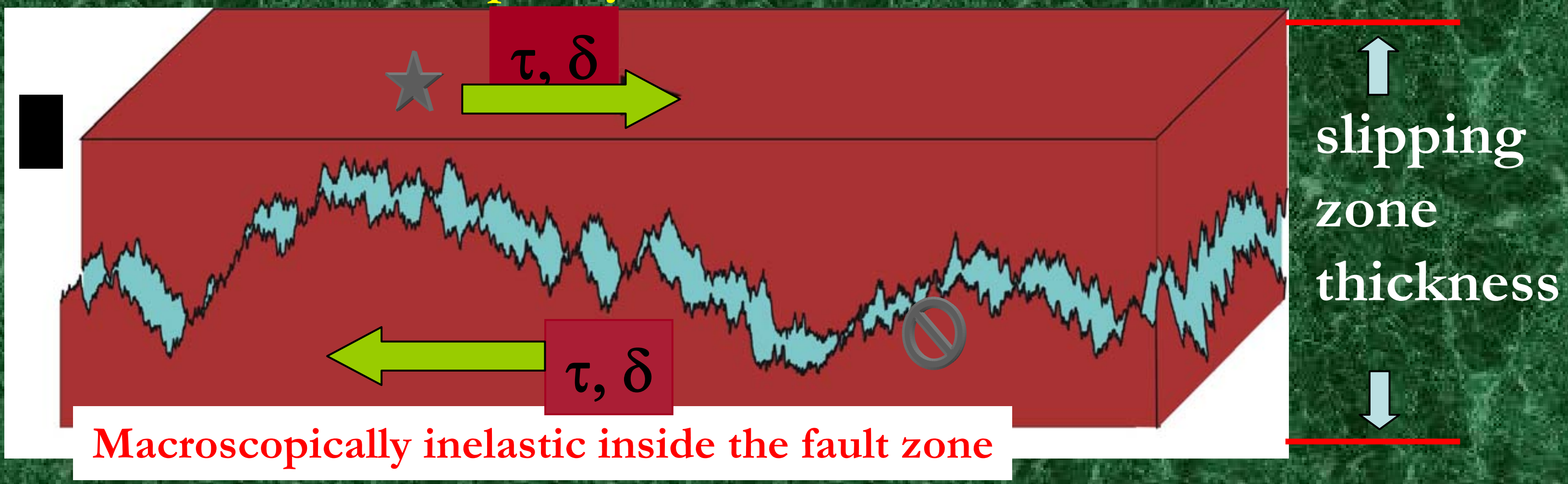
- Most of our understanding on earthquake dynamics relies on frequency-dependent seismological observations
- Geophysical observations allow us only to constrain macroscopic physical quantities (stress, slip, slip velocity,…)
- Friction should be considered in a macroscopic sense or as a phenomenological description of complex processes occurring within the fault zone

Macroscopically elastic outside the fault zone



The earthquake Energy Balance

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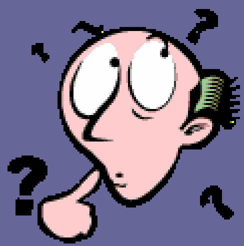
$$\boxed{\Delta W = E_{S_o} + \Delta E_{\Sigma}}$$

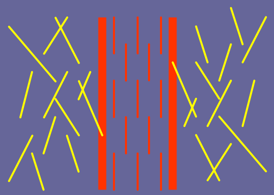
- E_{So} contains the radiated energy E_r and ΔE_{Σ} is the energy flux on the fault plane

Fracture Energy

Frictional Heat



$$\left\{ \begin{aligned} \Delta E_{\Sigma} &= E_G + E_F \\ \Delta E_{\Sigma} &= \Delta U_S + \Delta Q \end{aligned} \right.$$



a scale problem ??

Surface Energy

Heat

- ΔE_{Σ} contains the energy consumed in overcoming fault friction and the energy consumed for expanding the rupture surface area (that is to maintain the rupture front propagation), but it also contains surface energy and heat

The Macroscopic Frictional Work

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- We have defined the macroscopic frictional work as the irreversible part of mechanical work, which is the work that does not go into elastic strain energy and kinetic energy
- In a realistic fault zone model the macroscopic frictional work contains all the mechanical energy absorbed within the fault zone, including seismological fracture energy (i.e., breakdown work)

- Frictional Work rate $\tau_i \Delta \dot{u}_i = 2\dot{\gamma} + \Delta q$ **Kostrov & Das 1988**

local estimates

- Frictional work $\Im(\vec{\xi}) = \int_0^{t_m} \tau_i \Delta \dot{u}_i \, dt = \int_o^{D_t} \tau_i \, d(\Delta u_i)$

- Total Frictional work $\Delta E_\Sigma = \iint_\Sigma dS \int_0^{t_m} \tau_i \Delta \dot{u}_i \, dt = \iint_\Sigma dS \int_o^{D_t} \tau_i \, d(\Delta u_i)$

Cocco, Spudich, Tinti, AGU Monograph, 2006

Fracture Energy & Breakdown Work

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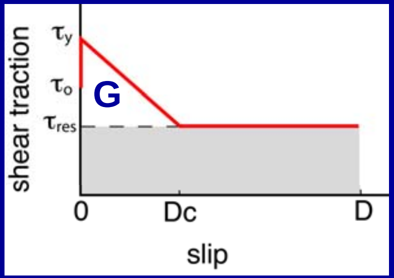
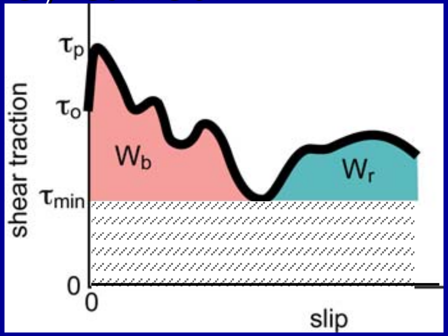
- Fracture energy (G′) is commonly associated with the area below the shear traction curve and above the residual or minimum stress level

$$G' = G'(\delta) = \int_0^{D_c} \left[\tau(\delta') - \tau_{res}\right] d\delta'$$



- Tinti et al. (2005) defined the excess of work over the minimum traction achieved during slip, which they called breakdown work

$$W_b = \int_0^{T_b} \left(\vec{\tau}(t) - \vec{\tau}_{min}\right) \cdot \dot{\vec{\delta}}(t)\, dt$$



$$W_b \propto M_o^{0.59} \qquad W_b \propto \Delta u^2 \qquad W_b \propto g(v_r)$$

Tinti et al., JGR, 2005; Cocco et al, AGU Monograph, 2006

A thermo-dynamical description of dissipation potential

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- The macroscopic frictional work is the total intrinsic power of dissipation of the whole fault zone and the breakdown work is its measurable portion
- Seismological estimates of breakdown work represent the only measurable portion of the mechanical work dissipated within the fault zone
- They should also contain the energy lost outside the principal slipping zone for off-fault cracking and plastic deformation
- Because the fault zone volume is replaced by a fictitious contact surface of zero thickness, this mathematical surface is characterized by a phenomenological friction or contact law which is supposed to capture the main features of dynamic fault weakening during the earthquake rupture

Surface Energy of the whole FZ

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- The surface energy produced during rupture propagation is (Chester et al., 2005):

$$U_s = (A_{SZ} + A_{DZ})\cdot \gamma \qquad [\mathrm{J\ m^{-2}}]$$

where A_{SZ} and A_{DZ} are the new surface per unit fault area (A_{SZ} and A_{DZ} are dimensionless) produced in the slipping zone and in the damage zone (i.e., wall rocks), respectively, and γ is the specific surface energy.

Comparison & Scaling

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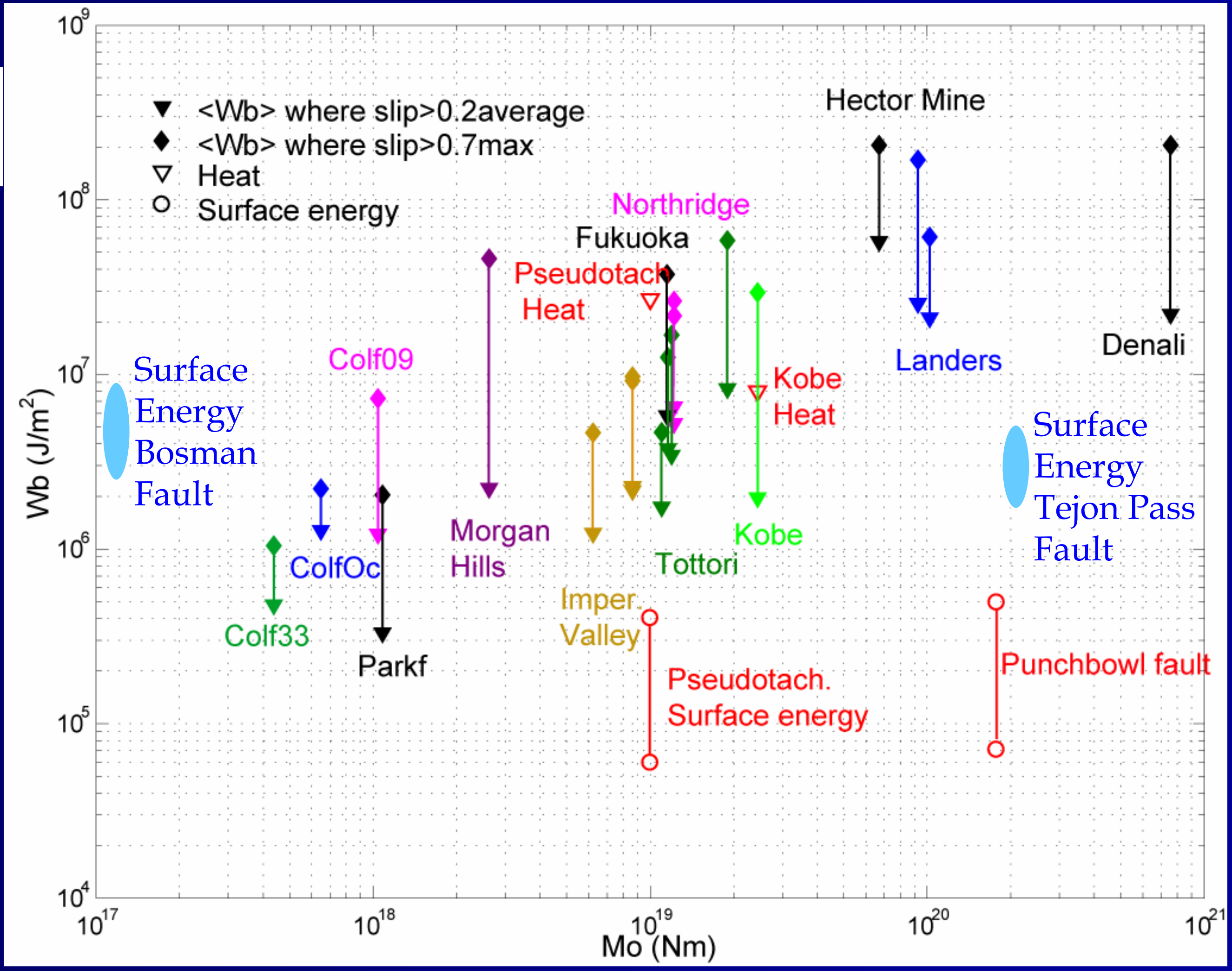
W_b



Conclusions #1:
A model for interpreting seismological observations

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- Seismological observations, which depend on selected frequencies and wavelengths, can only provide an estimate (lower bound) of a surface dissipation potential
- The proposed model allows the physically consistent interpretation of breakdown work (seismological fracture energy) as the only measurable portion of the total macroscopic intrinsic power of dissipation
- The main variables can not be related directly to the physics of processes at the micro- and meso-scales
- At this macro-scale surface energy is negligible, but not seismological fracture energy
- The mechanical work partitioning between surface energy and other dissipative mechanisms does not affect earthquake dynamics

Conclusions #2:
Energy budget for earthquake dynamics

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- We need to identify and interpret the crack driving force for the earthquake rupture in this phenomenological framework
- At this level of macroscopicity energy has to be absorbed near the virtual rupture front and shear stress is finite at the virtual crack tip and over the macroscopic slipping region
- We apply a SW model to the virtual mathematical plane

$$W_b = G' \stackrel{def}{=} g(v_r) G_{stat} = g(v_r) \frac{K_i^2}{2\mu}$$

$$G' \neq \gamma_{eff}$$

Implications
from this phenomenological description

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- The partitioning between measurable seismological fracture energy and the remaining intrinsic power of dissipation is only necessary to identifying the crack driving force
- The rupture velocity imaged from modeling seismological data is a macroscopic parameter
- Seismological fracture energy is a scale dependent parameter and it cannot be associated with any physical process occurring at smaller scales
- The use of $g(v_r)$ for real earthquakes is limited to the validity of this macroscopic description (all the strain rate is virtually localized on the mathematical plane

Physical interpretation of a phenomenological contact law

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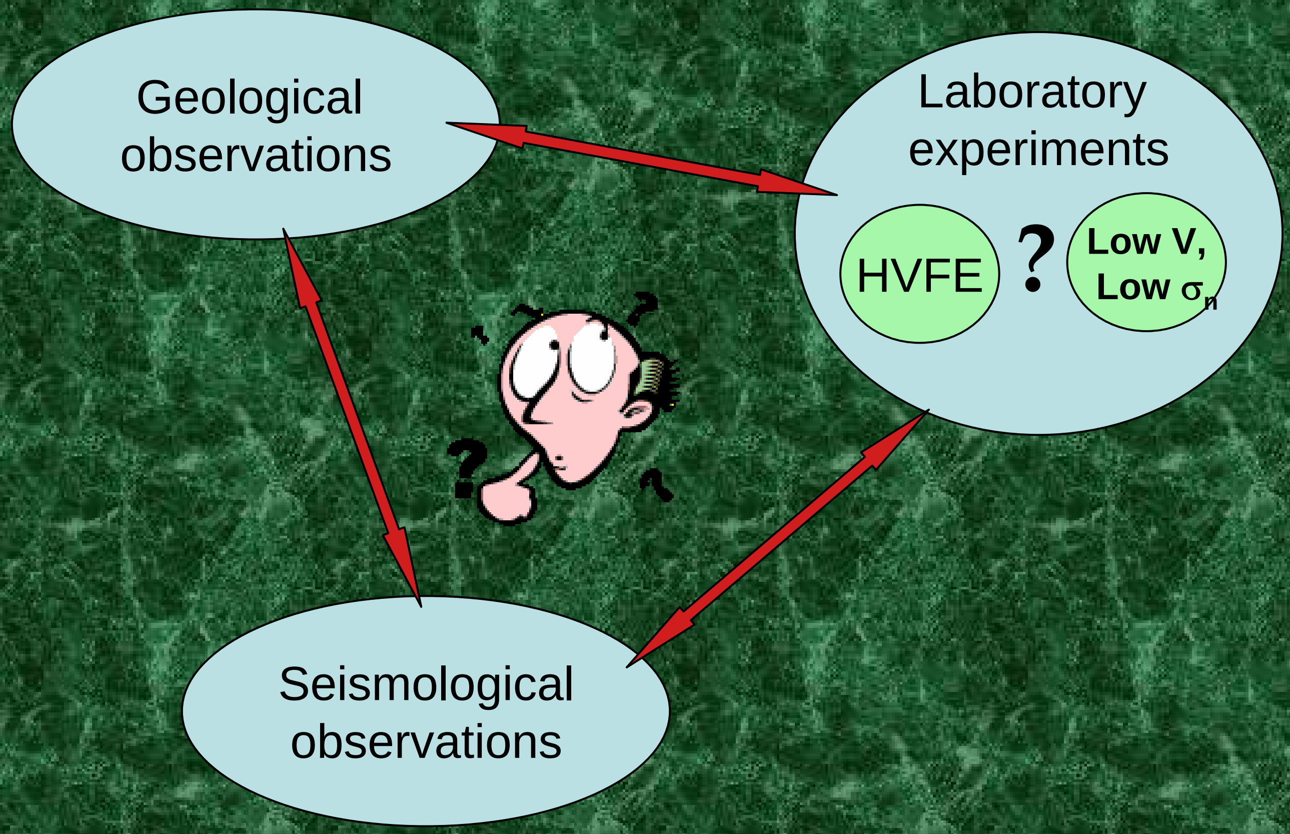
- There are other issues that need a careful discussion:
  - Extrapolating results from lab experiments to real earthquakes
  - Interpreting R&S friction in this context
  - Interpreting D_c from seismology and comparing it with lab measures (HVFE)
  - Laboratory experiments: HVFE vs classic friction, bare surface vs gouge material, dry vs wet ………………


Geological observations
Laboratory experiments
HVFE
?
Low V, Low σ_n
Seismological observations


Thank you
for your attention

Conventional stick slip friction

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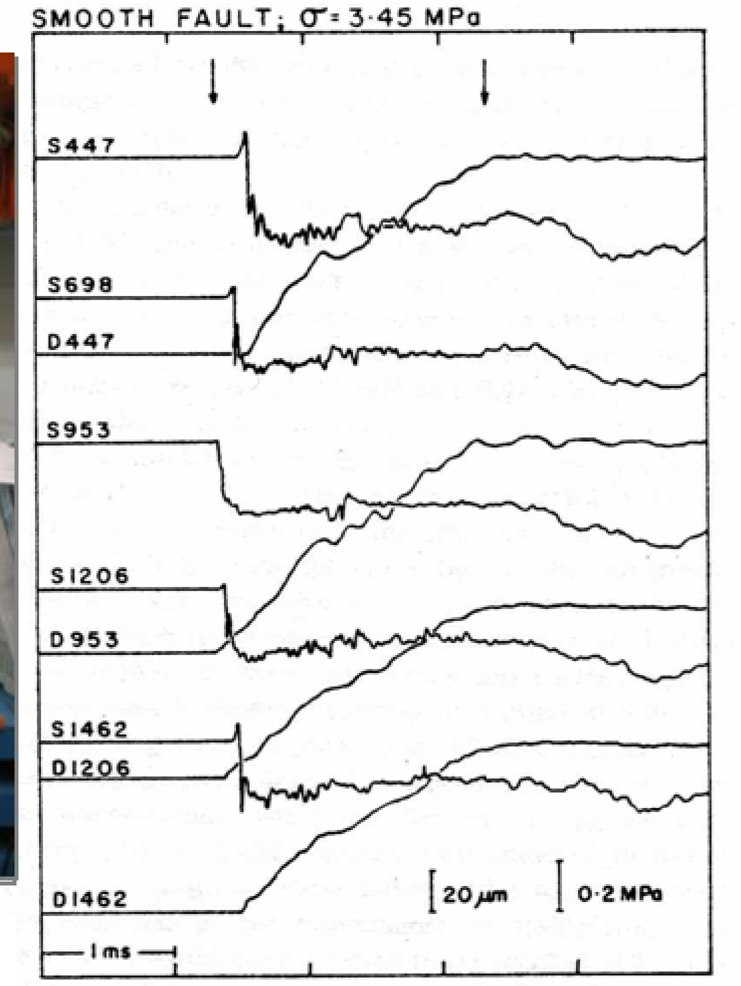
small slip, relatively low slip speeds, negligible shear heat



(Okubo and Dieterich, 1984)

Observation #2
Surface Energy from Geology

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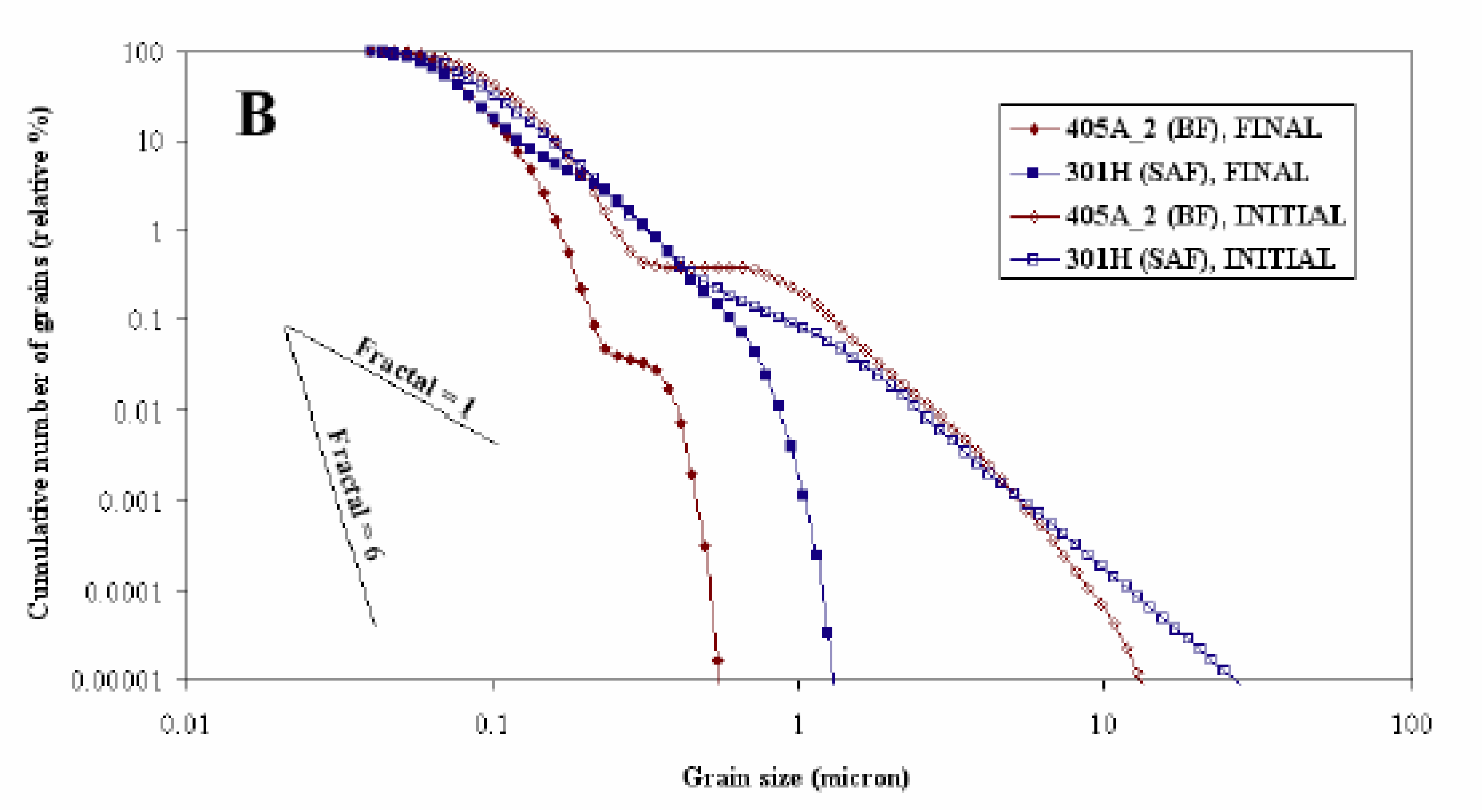
Wilson et al. (2005) determined the particle size distributions and total surface area of the rock flour in the Bosman fault and in the pulverized granite zone of the San Andreas fault. Using a single-crystal fracture energy of about 1 J/m^2, they estimated total surface energy of the fractured rock.



A thermo-dynamical description of dissipation potential #2

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- The seismological breakdown work estimates have to be interpreted in terms of a virtual surface dissipation potential (or equivalently of a surface density function)